Wave Breaking Influence in a Coupled Model of the Atmosphere-Ocean Wave Boundary Layers Under Very High Wind Conditions

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LONG-TERM GOALS

The long-term goals are to contribute improvements in current physical understanding and modeling of interfacial processes fundamental to air-sea interaction fluxes, particularly those involving wave breaking and spray droplet production. These advances will improve the reliability of operational sea state and ocean weather forecasting models, particularly for severe to extreme sea states.

OBJECTIVES

This project seeks to improve the reliability of air-sea interfacial flux parameterizations in coupled sea state/marine weather forecasting models, with a particular focus on refining and incorporating the role of wave breaking and sea spray in severe conditions. Our approach is through developing more realistic parameterizations for breaking occurrence and strength, and sea spray/spume source functions and validating them in our test-bed models. Our goal is then to implement these improvements in a coupled COAMPS/WaveWatch III model for operational use.

APPROACH

Our approach is to build substantially on our accumulated expertise in sea surface processes and air-sea interaction (Banner) and numerical weather modelling (Leslie) to identify and fill fundamental knowledge gaps in order to improve the modelling accuracy for severe marine meteorological events such as hurricanes. Such improvements depend critically on gaining a more complete understanding of severe sea state phenomena linked to wave breaking – increased surface drag and sea spray production. Quantifying the distribution of wave breaking events has progressed within this project as a result of an intensive collaboration with D. Farmer and J. Gemmrich (IOS, Canada) in FY01. From their storm wave datasets, a robust threshold behavior was identified in terms of the local wave spectral saturation level $B(f)$ for wave breaking at different scales (Banner et al, 2002, hereafter BGF02). The spectral saturation $B(f) = (2\pi)^4 f^5 F(f)/2g^2$ for the wave energy spectrum $F(f)$. This result has proven very useful in our ongoing effort to parameterize wave breaking spectrally in wind-wave models, and underpins our new spectral source term formulations for the wave energy dissipation rate. It is also being used in the spray/spume production term we are formulating in collaboration with C. Fairall (NOAA).

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Our model development has focused on refining full-bandwidth computations of the directional wave spectrum and its tail region using 'exact' versions of the nonlinear wave-wave interaction source term in the radiative transfer equation for the wave field. We have concentrated on fetch-limited growth cases, as this is where data exists. Such an approach is necessary to ensure that the modelled spectral saturation levels and dissipation rates are consistent with observed levels. This is essential for predicting spectral breaking wave properties, and for reliable calculations of the enhanced fluxes between the atmosphere and ocean associated with wave breaking events. A successful outcome in this context is needed to underpin future operational versions of our spectral wave breaking models. Our effort has focussed strongly on formulating, implementing and refining modeling strategies for (a) extracting the relevant wave breaking parameters, (b) calculation of wind stress/roughness length enhancements and updating the surface layer winds accordingly. For (a), we have significantly refined our capabilities reported previously for calculating the spectral density of mean breaking wave crest length/unit area. This is one of the primary goals in our modeling effort, as this quantity is central to the prediction of breaking wave enhancements to the wind stress, and development of a spray/spume source function based on sea state rather than the wind field. Our progress builds on refinement of the form of S_{ds} proposed by Alves and Banner (2002) [hereafter AB02] and on advances in predicting wave breaking probabilities at different wave scales in BGF02. The AB02 form of S_{ds} was upgraded to incorporate the observed BGF02 breaking saturation threshold. We have also investigated various refinements to its spectral distribution in order to provide a better match to the wind input source function S_{in} at higher wavenumbers, and to recently available published spectral wave breaking observations of Melville and Matusov (2002) [hereafter MM02]. To progress, we have had to invest very considerable effort evaluating various versions of the 'exact' S_{nl} code and propagation schemes to ensure accuracy and minimise computational instabilities that can develop at higher wavenumbers.

WORK COMPLETED

1. Wind-wave evolution modelling

In brief, during FY03 we continued our main effort on model development. We refined our capability for computing the directional wave spectrum, with particular emphasis on the spectral tail region out to frequencies of up to 3Hz. This involves large numbers of very lengthy computations, associated with the well-known complexity of the exact form of S_{nl}. We concentrated our attention on wind speeds in two ranges (a) 7-14 m/s and (b) 30 m/s. For (a), direct comparisons were made with the 1D transect wave spectra and the breaking crest length spectra of MM02, and recent results are presented below. For (b), the aim was to demonstrate stable model tail behavior for gale force wind speeds, which was achieved. A detailed investigation was made of the new analysis technique (see 2. below) that we developed for determining wave crest passage rates from ocean wave data needed for our modeling effort on breaking waves.
In greater detail, we formulated a number of variants of the unknown spectral wave energy dissipation rate source term, S_{ds}, each with a nonlinear dependence on the saturation ratio. Sd0 and Sd2 are two variants with different wavenumber weightings. We investigated these in the spectral wave evolution equation for fetch-limited conditions, using a full spectral bandwidth, i.e. free of any imposed spectral tail. The nonlinear transfer source term S_{nl} used was the standard Resio-Tracy exact form, as this gave the best stability. The wind input source term S_{in} was based on a modified parameterisation of Yan (1987). It embodies the traditionally- observed dependences on wind parameters linear near the spectral peak and quadratic in the spectral tail. It also provides input to the wind for waves outrunning the wind. Modeled directional spreading properties compare very favorably with the data of Hwang et al. (2000).

Throughout these calculations, our results for integral wave spectral properties such as mean energy and peak frequency achieve a very close correspondence with the observed evolution behavior in Kahma and Calkoen (1992). We also obtain very close model agreement, both level and spectral slope, with the high wavenumber tail of the 1-D transect spectrum observed by MM02 (not shown here). Following on from these validations, we made extensive calculations of the spectral density of breaking crest length per unit area, and how these breaking wave spectra change with wind speed and wave age, which are particularly demanding tests. We compare our model results with the available observational data of MM02, with very mature wind sea conditions and winds of 9.8 m/s and 13.6 m/s. From the spectral evolution calculations, of particular importance are the spectral distributions of dissipation rate, S_{ds}, spectral saturation, B, and the breaking crest length/unit area of waves travelling with speeds in (c, c+dc), $\Lambda(c)$. Our calculations highlight, for the first time, the sensitivity of the $\Lambda(c)$ predictions to the imposed S_{ds}. As there are no available direct spectral dissipation rate observations, the results of MM02 for $\Lambda(c)$ provide the first independent measurement that can be used to decide between S_{ds} formulations. This has underpinned our systematic investigation of the impact of competing S_{ds} formulations. For such a complex nonlinear system, this represents a very challenging task. Progress on this fundamental problem is reported under 'Results'.

2. Riding wave analysis

For 1., we developed a novel time series analysis technique ('riding wave removal' [RWR] method) for counting riding wave crest passage rates needed to model breaking waves. This technique counts, and also characterises the geometrical properties (e.g. steepness) of, the short wind waves riding on longer waves. We investigated these properties for a number of field data sets (North Sea, Black Sea, N. Pacific) for young and old wind seas. This technique can provide useful 'physical roughness' data complementary to the usual spectral data, and a paper is in preparation.

3. New wind input source function

A new wind input source function has been proposed (Donelan et al, 2003). This is based on Lake George data for very young sea conditions, which shows an abrupt transition of the near-surface air flow from attached to separated, when the waves become sufficiently steep. This is accompanied by a marked reduction in the input momentum and energy fluxes from the wind. However, the strongly discontinuous nature of this form of wind input term presents new modeling challenges that we felt should await further progress with 1. before implementation.

4. Improved spume/spray droplet source term

In collaboration with two other CBLAST PI's: C. Fairall and W. Asher, an exploratory laboratory experiment was staged at the UNSW Water Research Laboratory in Sydney, Australia. The primary aim was to seek a dependence of spume droplet flux on breaking wave properties rather on the wind speed. This is the basis of an initial wave breaking/turbulent flow model of spume droplet production in terms of the surface dissipation rate of breaking waves developed with C. Fairall. Droplet measurements were made with Fairall's CIP probe and with Asher's TSI Droplet analysis system as a precursor to their aircraft deployment in the CBLAST Hurricane missions. Typically, our runs had friction velocities in the range 1.2-1.8 m/s in conjunction with paddle-initiated wind waves with frequencies in the range 1.36-1.6 Hz. Water salinity was varied from 0 to 25 parts per thousand. The breaking wave properties were measured with a small directional array of surface-piercing wire impedance gages each sampled at over 2000 Hz, in order to capture the surface fine structure. Overall, we successfully gathered a comprehensive data set on droplet properties and the associated wave surface microstructure. Analysis of the breaking wave data to extract a consistent measure of ‘surface disturbance energy levels’ is complex and currently in progress.

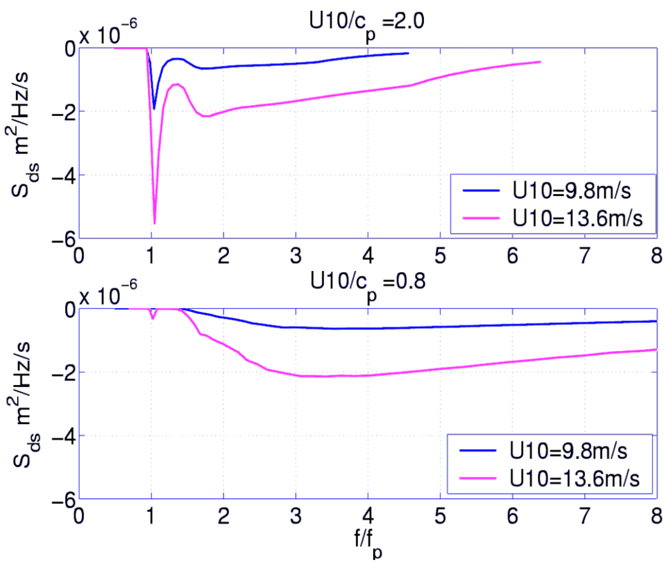
5. Coupling wind profile and sea surface aerodynamic roughness changes

A Fortran code has been developed to allow the iterative computation of the wind stress and wave spectrum in response to changes due to breaking-induced wave drag. This approach is based on the calculation of wave breaking properties from the wave spectrum, the consequent enhanced wave drag and the adjustment of the aerodynamic roughness length z_0 in the assumed logarithmic mean velocity profile for the surface layer wind field. In turn, the wave spectrum is modified in response to the updated wind profile. This code awaits introduction into the coupled test-bed model once the breaking wave extraction algorithm in the model has been optimised against available data.

RESULTS

Wind wave modelling and spectral breaking wave distributions

Fig.1 shows the excellent correspondence between modeled and observed evolution for the key integral wave properties, using Sd0 as the form of S_{ds}. Similar results were obtained with Sd2. Fig.2 shows the substantial wind speed and wave age variation resulting from our Sd2 dissipation rate source term spectrum. The wind speeds match those in the old wind sea observations of MM02.



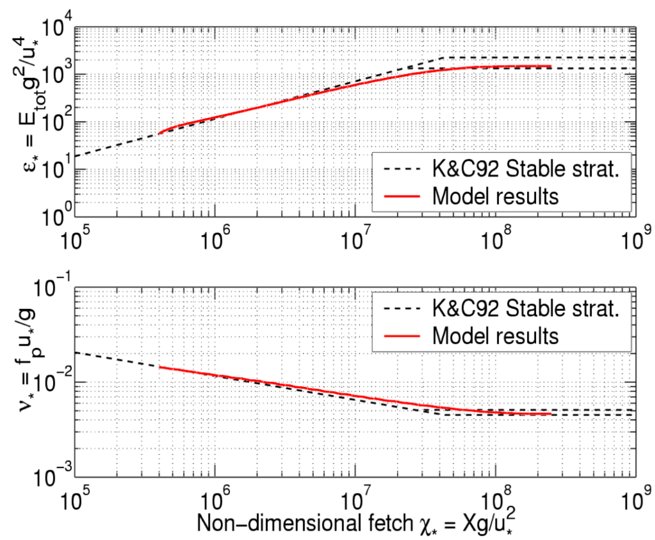


Fig. 1 Comparison of modeled and observed Kahma-Calkoen (1992) integral wave properties for fetch-limited evolution, using our saturation threshold dissipation rate source term. Non-dimensional wave energy ε_* (upper panel) and peak frequency ν_* (lower panel) against non-dimensional fetch χ_*, based on u_* scaling.

Fig. 2 These panels show the strong wind speed variation of modeled dissipation rate S_{ds} spectra computed using Sd2 for U_{10} = 9.8m/s and 13.6 m/s for young wind seas (upper panel) and old wind seas (lower panel). The horizontal axis is frequency normalized by the frequency at the peak of the wave spectrum.

It is only when the key spectral tail properties are compared can large differences be seen between the S_{ds} source terms. Fig.3 below shows the spectral saturation B for U_{10} ~10 m/s using the two forms Sd0 and Sd2, as a function of f/f_p, compared with the saturation data from the North Sea. Sd2 captures the levels and overall shape of the observations, while Sd0 shows a non-physical decrease above the spectral peak. Fig.4 shows the sensitivity to the choice of S_{ds} of our model computations of $\Lambda(c)$, the spectral density of breaking crest length/unit area of sea surface, expressed as a function of the phase speed *c*. The sea state conditions matched those in the observations of MM02. The computed results using Sd2 follow the spectral steepness of the MM02 observations more closely. We note that MM02 only include growing breaking crests in their analysis, and hence neglect the dissipation associated with relaxing breaking crests. This is consistent with our systematically higher spectral levels compared with MM02. A key issue is to optimize the wave age and wind speed performance of S_{ds} in predicting $\Lambda(c)$. Sea state data gathered during the recent CBLAST hurricane missions will be crucial to this goal.

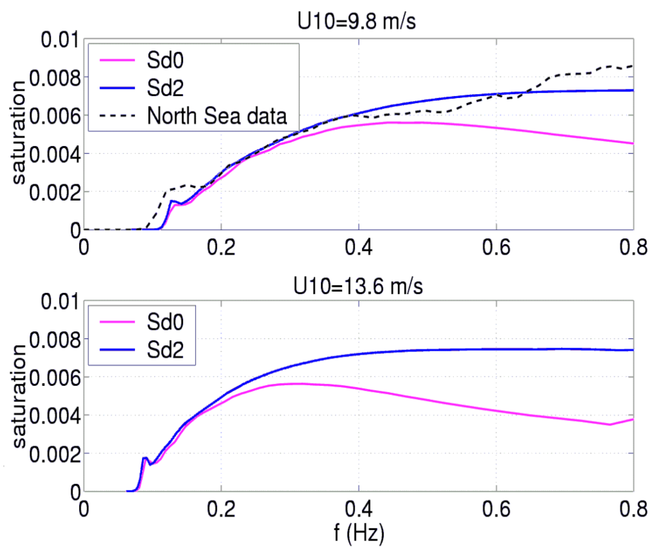


Fig. 3 Comparison of computed azimuthally-integrated spectral saturation B as a function of f/fp for U10 = 9.8 m/s (upper panel) and 13.6 m/s (lower panel) using two versions (Sd0 and Sd2) of the spectral dissipation source term Sds. A typical saturation spectrum for 9.8 m/s observed in the North Sea is shown for comparison.

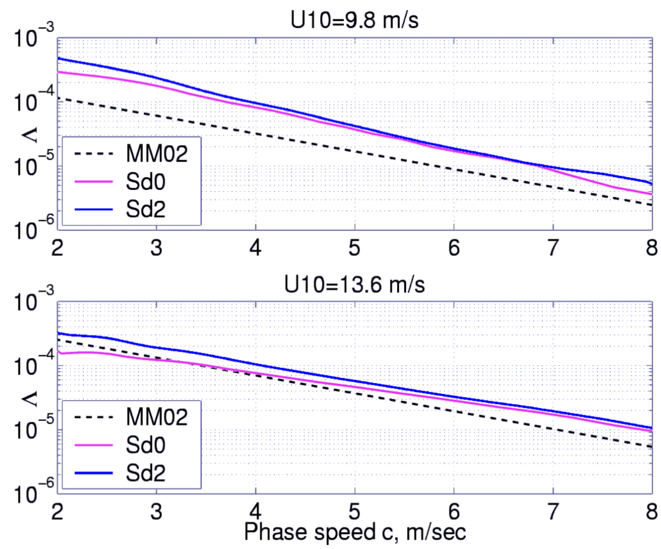


Fig. 4 Computations of $\Lambda(c)$, the spectral density of breaking crest length/unit area as a function of phase speed c, using two versions (Sd0 and Sd2) of the spectral dissipation source term S_{ds}. Wind speeds U_{10} are 9.8 m/s (upper panel) and 13.6 m/s (lower panel) and seas are very old (U_{10}/C_p~0.8). The MM02 observations for each wind speed are shown for comparison.

IMPACT/APPLICATIONS

Enhanced scientific understanding of severe sea state air-sea interfacial processes, particularly wave breaking and spray/droplet production rates, will provide more reliable parameterizations of these processes and closely related air-sea fluxes. These improved parameterizations will increase the reliability of operational sea state and marine meteorological forecasts, especially during severe marine weather conditions. A particular benefit for smaller vessels will be routine forecasts of occurrence rate of dangerous breaking waves.

RELATED PROJECTS

The ONR project *Source Term Balance for Finite Depth Wind Waves* (Young, Banner and Donelan) includes a strong focus on the influence of steep waves and wave breaking on the wind input source function in strongly forced, constant depth, shallow water environments. This data set has been analyzed and initial papers on the methodology and results have been submitted, with other papers in preparation [e.g. Donelan et al, 2003a,b; Young et al, 2003]. We have begun exploring these outcomes in this project.

REFERENCES

Alves, J.H.G.M. and Banner, M.L. 2002 *Performance of a spectral saturation-based dissipation source term in modeling the fetch-limited evolution of wind-wave*, J. Phys. Oceanogr. 33, 1274-1298.

Banner, M.L., Gemmrich, J.R. and Farmer, D.M. 2002 *Multiscale measurements of ocean wave breaking probability.* J. Phys. Oceanogr. 32, 3364-3375

Hwang, P.A., D.W. Wang, E.J. Walsh, W.B. Krabill & R.W. Swift, 2000 Airborne measurements of the wavenumber spectra of ocean surface waves. Part II: Directional distribution. *J. Phys. Oceanogr.*, 30, 2768-2787.

Kahma, K.K. and Calkoen, 1992 *Reconciling discrepancies in the observed growth of wind-generated waves*. J. Phys. Oceanogr. 22, 1389-1405.

Melville, W.K. and Matusov, P., 2002: *Distribution of breaking waves at the ocean surface*. Nature 417, 58-63.

Yan, L., 1987: An improved wind input source term for third generation ocean wave modelling. Sci. Rept. WR-87-8, KNMI, De Bilt, the Netherlands, 10pp.

PUBLICATIONS

M. L. Banner*:*

Babanin, A.V., Young, I.R and Banner, M.L. 2001 Breaking probabilities for dominant surface waves on water of finite constant depth. *J. Geophys. Res*. 106, C6, 11,659-11,676. [published, refereed]

Song, J. and Banner, M.L. 2002 On determining the onset and strength of breaking for deep water waves. Part 1: Unforced irrotational wave groups. *J. Phys. Oceanogr*. 32, 2541-2558. [published, refereed]

Banner, M.L. and Song, J. 2002 On determining the onset and strength of breaking for deep water waves. Part 2: Influence of wind forcing and surface shear. *J. Phys. Oceanogr***.** 32, 2559-2570. [published, refereed]

Banner, M.L., J.R. Gemmrich and D.M. Farmer, 2002: Multiscale Measurements of Ocean Wave Breaking Probabilit*y. J. Phys. Oceanogr*. 32, 3364-3375. [published, refereed]

Alves, J.H., D.A. Greenslade and M.L. Banner, 2002: Impact of a saturation-dependent dissipation source term on wave hindcasts in the Australian region. The *Global Atmosphere and Ocean System*, 8, 239-267. [published, refereed]

Alves, J.H. and Banner, M.L. 2003: Performance of a spectral saturation-based dissipation source term in modeling the fetch-limited evolution of wind-wave*. J. Phys. Oceanogr*. 33, 1274-1298. [published, refereed]

Alves, J.H., Banner, M.L. and Young, I.R. 2003: Revisiting the asymptotic limits of fully developed seas. Part I: Reanalysis of the Pierson-Moskowitz database*. J. Phys. Oceanogr*., 33, 1301-1323. [published, refereed]

Peirson, W.L. and M.L. Banner, 2003: Aqueous surface layer flows induced by micro-breaking wind waves. *J. Fluid Mech*. 479, 1-38. [published, refereed]
Donelan, M.A., A.V. Babanin, I.R. Young, M.L. Banner, and C. McCormick, 2003: Wave follower measurements of the wind input spectral function. Part I. Measurements and calibrations. Submitted to the Journal of Atmospheric and Ocean Technology.
Young, I.R., M.L. Banner M.A., Donelan, A.V. Babanin, W.K. Melville, F. Veron and C. McCormick, 2003: An integrated study of the wind wave source term balance in finite depth water. Submitted to the *Journal of Atmospheric and Ocean Technology.*
Donelan, M.A., A.V. Babanin, I.R.Young and M.L. Banner, 2003: The wind input source function for shallow water waves. Part 2. Submitted to the *Journal of Physical Oceanography.*
Song, J. and M.L. Banner, 2003: On the influence of mean water depth and a subsurface sand bar on the onset and strength of wave breaking. *Submitted to the Journal of Physical Oceanography.*

L.M. Leslie:

Books:

Leslie, LM (with G. Peng and Y.Shao), (2002): *Environmental Modeling and Prediction*, Springer, 480pp, ISBN 3-540-67422-5. [published, refereed]

Book Chapters:

Leslie, LM, (2003): "High-resolution Atmospheric Modeling. Part I: Theory". Ch. 6, *Impact Science*. Ed. J. Nicholls and B. Pailthorpe. Tandem Group Pty. Ltd., ISBN: 1 86487 551 8, 193pp. [published, refereed]
Leslie, LM, (2003): *High-resolution Atmospheric Modeling. Part II*: *Applications*. Ch. 7, *Impact Science*. Ed. J. Nicholls and B. Pailthorpe. Tandem Group Pty. Ltd., ISBN: 1 86487 551 8, 193pp. [published, refereed]

Journal Publications:

Leslie, LM, (2003): Mathematics in Meteorology, *Notices of the American Mathematical Society* [In Press]
Leslie, LM, Speer, MS, Buckley, BW and Qi, L, (2003): Recent developments in supercell prediction. *Meteor. Atmos. Phys*., 87, [In press]
LeMarshall, JF, LM Leslie, R. Seecamp, and A. Rea, (2003): Reducing large forecast errors in tropical cyclone predictions using the 4D-VAR assimilation of high-resolution satellite and radar data. *Aust. Meteor. Mag*., 52, [In Press].
Leslie, LM and MS Speer, (2003) Modelling a coastal ridging event over south-eastern Australia. *Meteor. Apps.,* **11**, [In Press]
Liu, S, LM Leslie, MS Speer, R. Bunker, and X, Mo, (2003): The effects of bushfires on hydrological processes using a paired-catchment analysis, *Meteor. Atmos. Phys*. [In Press]
Buckley, BW and LM Leslie, (2003): The impact of observational technology on climate database quality. *J. Climate,* **16***,* 2640-2645. [published, refereed]
Speer, MS, LM Leslie, and L.Qi, (2003): Numerical Prediction of Severe Convection: Comparison with Operational Forecasts, *Meteor. Apps.,* 10, 11-19. [published, refereed]
Leslie, LM, MS Speer,and L Qi, (2003) Prediction of Extreme Rainfall for the Coffs Harbour Catchment. *Aust. Meteor. Mag.*, 52, 95-100. [published, refereed]
J. LeMarshall, JF, LM Leslie, R. Seecamp and A.Rea, (2003): Remote sensing applications in meteorology: A review, *MAUSAM*, 54, 1-12. [published, refereed]
Leslie, LM, JF LeMarshall and WL Smith, (2002): Mesoscale initialization using advanced sounder data, *Adv. Space Res.,* 30*,* 2479-2486. [published, refereed]
Shao, Y, E Jung and LM Leslie (2002): Numerical prediction of northeast Asian dust storms using an integrated wind erosion modeling system, *J. Geophys. Res.*, 107, 1493-1516. [published, refereed]

LeMarshall, JF, LM Leslie and WL Smith, (2002): Initialization of a NWP model using high spatial and temporal resolution satellite data, *Adv. Space Res.*, 30, 2441-2446. [published, refereed]
LeMarshall, JF, GA Mills, R. Seecamp, N. Pescod, LM Leslie and A. Rea, (2002): The estimation of high density atmospheric motion vectors and their application to operational NWP, *Australian Meteor. Mag*., 51, 173-180. [published, refereed]
LeMarshall, JF, LM Leslie and RF Abbey (2002): Tropical cyclone track and intensity prediction: The generation and assimilation of high density satellite-derived data, *Meteor. Atmos. Phys.*, 80, 43-57. [published, refereed]
Leslie, LM, RF Abbey, MS Speer and TCL Skinner, (2002): Intense tropical cyclogenesis over the northwest Australian region in 1998/1999: Causal factors, *Meteor. Atmos. Phys*., 80, 89-101. [published, refereed]
Morison, RP, Leslie, LM and MS Speer (2002): Atmospheric modeling of air pollution as a tool for environmental prediction and management, *Meteor. Atmos. Phys*., 80, 141-151. [published, refereed]
Speer, MS, and LM Leslie (2002): The prediction of two cases of severe convection: implications for forecast guidance, *Meteor. Atmos. Phys*., 80, 165-175. [published, refereed]
Leslie, LM and MS Speer (2001): Comments on statistical single-station short-term forecasting of temperature and probability of precipitation, *Wea. Forecasting*, 16, 765-767. [published, refereed]
Nagata, M, LM Leslie and 19 others, (2001): A model intercomparison of tropical cyclone intensity and track prediction, *Bull. Amer. Meteor. Soc.*, 82, 2007-2020. [published, refereed]
Qi, L and LM Leslie (2001): Cut-off low pressure systems over southern Australia: a numerical modeling study and sensitivity experiments, *Aust. Meteor. Mag*., 50, 183-194. [published, refereed]
Buckley, BW, LM Leslie and Y Wang (2001): The Sydney hailstorm of April 14, 1999: Synoptic description and numerical simulation, *Meteor. Atmos. Phys*., 76, 167-182. [published, refereed]
Speer, MS, LM Leslie, RP Morison, W Catchpole, R Bradstock and R Bunker (2001): Modeling fire weather and fire spread rates for two bushfires near Sydney, *Aust. Meteor. Mag*, 50, 241-246. [published, refereed]
Nagata, M, LM Leslie and 20 others, (2001): A mesoscale model intercomparison: A case of explosive development of a tropical cyclone, *J. Meteor. Soc. Japan*, 79, 999-1033. [published, refereed]

HONORS/AWARDS/PRIZES

In 2002, Michael L. Banner of the University of New South Wales, Sydney, Australia was awarded the Sverdrup Gold Medal of the American Meteorological Society. The citation was “for advancing the understanding of wave dynamics, especially wave breaking and the role of waves in air–sea interaction."
In 2003, Michael L. Banner of the University of New South Wales, Sydney, Australia was made a Fellow of the American Meteorological Society.